Naval Research Laboratory

Washington, DC 20375-5320

NRL/MR/6750--99-8349

The WIND-HAARP-HIPAS Interferometer Experiment

P. Rodriguez and M. J. Keskinen
Charged Particle Physics Branch
Plasma Physics Division

E. J. Kennedy
Transmission Technology Branch
Information Technology Division

Sa. Basu
Air Force Research Laboratory, Hanscom AFB, MA

M. McCarrick, J. Preston, H. Zwi, and M. Engebretson
Advanced Power Technologies, Inc., Washington, DC

A. Wong and R. Wuerker
University of California, Los Angeles, CA

M. L. Kaiser and M. D. Desch
Goddard Space Flight Center, Greenbelt, MD

K. Goetz
University of Minnesota, Minneapolis, MN

J.-L. Bougeret and R. Manning
DESPA, Observatoire de Paris, Meudon, France

April 22, 1999

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave Blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 22, 1999	Interim Report

4. TITLE AND SUBTITLE

The WIND-HAARP-HIPAS Interferometer Experiment

5. FUNDING NUMBERS

JO - 67-7324-A9

6. AUTHOR(S)

P. Rodriguez, E.J. Kennedy, M.J. Keskinen, Sa. Basu,* M. McCarrick,† J. Preston,† H. Zwi,† M. Engebretson,† A. Wong,‡ R. Wuerker,‡ M.L. Kaiser,§ M.D. Desch,§ K. Goetz,** J.-L. Bougeret,¶ and R. Manning¶

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6750--99-8349

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research, Arlington, VA
Air Force Research Laboratory, Hanscom AFB, MA
National Aeronautics and Space Admin., Centre National d'Etudes Spatiales

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Air Force Research Laboratory, Hanscom AFB, MA
†Advanced Power Technologies, Inc. Washington, DC
‡University of California, Los Angeles, CA
§Goddard Space Flight Center, Greenbelt, MD
**University of Minnesota, Minneapolis, MN
¶DESPA, Observatoire de Paris, Meudon, France

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	A

13. ABSTRACT *(Maximum 200 words)*

We report on the first experiment using two high power, high frequency transmitting facilities in a bistatic, interferometer mode. The HAARP and HIPAS facilities in Alaska radiated at 4525 kHz with total combined power of about 700 kW, in the direction of the WIND spacecraft. The WAVES experiment aboard WIND received the transmissions at a distance of about 25 earth radii. The experimental setup thus resembled Young's two-slit experiment. The expected interference pattern was observed, and at the distance of WIND, the fringes sizes were about 30 km peak to peak.

14. SUBJECT TERMS	15. NUMBER OF PAGES
High frequency radar Satellite receiver	12
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

The WIND-HAARP-HIPAS Interferometer Experiment

1. Introduction

The high latitude auroral region is known to have a wide range of scales of electron density structures resulting from plasma instabilities [Keskinen and Ossakow, 1983; Rodriguez and Szuszczewicz, 1984; Tsunoda, 1988; Keskinen and Rodriguez, 1998] driven by convective electric fields, field-aligned currents, and several other mechanisms. Scientific interest in these plasma structures is partly motivated by practical considerations such as fading of high frequency (HF) communications. During periods of intense geomagnetic activity, such effects can be significant [Weber et al., 1986]. The broader problem of coupling between magnetospheric and ionospheric structures also is related to the presence of the large-scale drivers of geomagnetic disturbances, such as the solar wind. The continuing study of plasma structures over various altitude ranges will benefit from new diagnostics made possible by high power radio waves. Recently, we have reported [Rodriguez et al., 1998] on initial experiments conducted with the HF Active Auroral Research Program (HAARP) near Gakona, Alaska, a joint Air Force/Navy project developing a new ionospheric diagnostic facility at high latitudes. In this report, we discuss an experiment that included the High Power Auroral Simulation (HIPAS) facility near Fairbanks, Alaska in bistatic configuration to form interference fringes at high altitudes. The scientific motivation is that the fringe pattern corresponds to smaller size "beamlets," that may stimulate or scatter from smaller scale density structures than would the main beam alone. We believe this is the first such experiment conducted.

2. Experiment Facilities

We briefly review the parameters of HAARP, HIPAS, and WIND/WAVES. The HAARP antenna array is still under construction; in our experiment 16 antennas were used with 32 transmitters (2 per antenna) to provide a total power of about 320 kW and effective radiated power (ERP) of about 4 MW. When completed (180 antennas), HAARP is designed to provide ERPs up to about 4 GW. The transmitting array is electronically steerable within 30° of the zenith, covering frequencies of transmission from 2.8 to 10 MHz. HIPAS consists of 8 cross-polarized dipoles operating at two frequencies, 2.85 and 4.53 MHz, with maximum power of about 800 kW. HIPAS pre-dates HAARP and has been used in many experiments involving high power wave interactions at auroral latitudes [Wong et al., 1990]. The WAVES HF receiver [Bougeret et al., 1995; Kaiser et al, 1996] includes a stepped frequency receiver covering 256 frequencies from 1.075 MHz to 13.825 MHz, in 50-kHz intervals, with 20-kHz bandwidth, and a detection threshold of ~7 nvolt/√Hz. The cycle time of the receiver is 16.192 seconds, with the

Manuscript approved March 29, 1999.

effective dwell time per frequency being 63 ms. For our experiment, the WAVES receiver was switched from its 256-step mode to a 1-step mode so as to sample the frequency of HAARP and HIPAS transmissions at maximum rate. The spin axis antenna, an 11-meter tip-to-tip length dipole, was used for reception.

3. Experiment Configuration

The HAARP and HIPAS sites are separated by 289 km. In order to form an interference pattern over that baseline, the basic requirement is that both HAARP and HIPAS transmit the same frequency and maintain the same relative phase between the two transmissions. Although the phases of the transmitted frequency cannot be locked together, the phase at each site is very stable, changing by no more than 1 part in several million, over periods of an hour or more. Thus, whatever intrinsic phase exists when the transmitters are turned on can be maintained for time periods exceeding the duration of the experiment. Therefore, we need have no knowledge of the exact phase difference between HAARP and HIPAS, only that the difference is stable for the duration of the experiment. Because HIPAS operates in only two frequency bands, we chose the frequency of 4525 kHz as the operating frequency; both HAARP and HIPAS can tune to this frequency and it corresponds to one of the WAVES receiver channels. For the nighttime experiment, 4525 kHz was also expected to be well-above the ionospheric critical frequency. A practical requirement is that both sites radiate approximately the same power so that interference nulls are small. This enhances detectability of the fringe pattern because the ratio of interference maximum to minimum is large. For our experiment, the HIPAS power was reduced to about 400 kW in order to remain approximately equal to the maximum HAARP power then available, about 300 kW. Thus, the basic conditions required to form an interference pattern were satisfied, and the experimental setup resembled the classic Young's two-slit experiment.

Figure 1 shows the orbit trajectory of WIND for the period 30 December 1996 to 1 January 1997, in solar ecliptic coordinates. The start and stop times of several different experiments conducted are indicated. In this report, we discuss results only from the third experiment, of 31 December 1996 between Universal Times (UT) of 0700-0800, when WIND was in night side of the earth at about 25 R_e. As seen from the transmitter sites, WIND was located at zenith angle of 40° and azimuth of 145°. The orbit phase of Figure 1 occurred about 6 weeks after the initial experiments reported in Rodriguez et al. [1998]. The campaign also included experiments with the Russian Sura transmitter, which we do not discuss in this report. Also shown are model plots of the plasmapause, magnetpause, and bow shock, to provide a geometric perspective of the experiments.

In Figure 2 we show the modulation timeline of transmitted power at 4525 kHz from each site, relative to the start of the experiment. The vertical axis is an offset scale; each timeline has a zero base representing the OFF state and an upper level representing the ON state. HAARP (upper timeline) was scheduled to turn on first, using an 30-sec ON-OFF amplitude modulation for the first 5 minutes. This pattern provides a signature to allow recognition of the transmitted waves in the WAVES measurements. HAARP then switched to a continuous wave (CW) ON mode for the next 45 minutes. At the 50-min point, HAARP was scheduled to turn OFF. The HIPAS transmitter (middle timeline) was scheduled to turn ON in CW mode at the 10-min point and remain ON until the 55-min point. In the last 5 minutes of the experiment (with HAARP in the OFF state) the HIPAS transmitter was amplitude modulated with 30-sec ON-OFF pattern. Between the 10-min and 50-min points, both HAARP and HIPAS radiate in CW mode. We thus expect that interference fringes would occur in the 10- to 50-min interval, when both sites were transmitting in CW mode. Also, we would expect to detect an increase in power level when both sites are transmitting simultaneously.

4. Experimental Results

In Figure 3, we show measurements of the WAVES receiver at 4525 kHz, at maximum rate of 0.06325 s between samples, for the 1-hour interval of the experiment. Wave amplitudes are in calibrated voltage spectral density. In the first and last 5-min intervals of the data plot, we can recognize the pattern of 30-sec ON-OFF modulations of HAARP and HIPAS. The presence of fairly strong amplitude fluctuations throughout the entire hour is similar to observations reported in the inital WIND-HAARP experiment. On the scale of the plot, these amplitude fluctuations are almost noise-like, However, they are not noise fluctuations, as can be seen by comparing with the true noise level sampled during the OFF periods of the data plot.

We calculate the expected fringe pattern at WIND using the standard formula for fringe intensity [Jenkins and White, 1976]

$$I_f \sim \cos^2[(\pi D/\lambda)\sin\theta]$$

where D is the baseline separation of the two transmitters, λ is the operating wavelength, and θ is the direction angle of WIND with respect to the baseline. For our configuration, D = 289 km, λ = 66.3 meters, and $\theta \sim 45°$. The angular fringe width (from one null to the next) is given approximately by $\Delta \sim \lambda/D \sim 0.013°$. At the distance R (~22.6 R_e) of WIND from the transmitter sites the fringe spacing becomes about $L \sim R\,\Delta \sim 33$ km. The relative velocity between the earth and WIND results in a sweeping of the antenna pattern (and the expected fringe pattern) past the satellite, at a relative angular rate of about 15.5° hr^{-1}. Based on these estimates, we would expect that a 33-km structure would occupy about 3.7 sec of the WAVES data, or about 60 samples. Examining the WAVES data in detail during the time interval UT 0710 to 0750, we find evidence of the expected fringe pattern.

In Figure 4, the upper plot shows the calculated time variation of the fringe intensity I_f, resulting from the sweep of the fringe pattern past the WIND spacecraft at the relative rate of 15.5° hr^{-1}. Below the calculated plot is 32 seconds of the data obtained in the time interval UT 0724:00 to UT 0724:32. The amplitude scales of the plots are offset for display purposes. The quasi-oscillatory variation of signal amplitude at 4525 kHz appears to be consistent with the calculated fringe pattern. Smaller scale amplitude fluctuations are also present in the data. Other intervals of the data between UT 0710 and 0750 exhibit the same fringe-like variations. It is apparent that the clarity of fringes varies and some positional drift may occur, however, the basic fringe pattern can be seen.. The impression is that the fringe structure is not static in space, but may drift. Such drifts may result from the effect of ionospheric and magnetospheric plasma density irregularities which move across the propagation path. It is also possible that the signal intensities of HAARP and HIPAS are sufficient to modify the intervening plasma through heating and affect the fringe pattern. Repeating experiments of this kind at varying power levels and frequencies will help to indentify thresholds for possible plasma modifications.

5. Summary and Conclusions

This experiment is one of a series in which diagnostics of the the ionosphere and magnetosphere may be done with high power HF transmitters on the ground in conjunction with space-based receivers. The interferometric experiment shows that HAARP and HIPAS can be used together to establish a structured beam with known fringe size. This may provide a method to interact directly with plasma irregularitites at a specific scale size. By using different frequencies we obtain different scale sizes in the structured beam. By varying the power density, we may expect that some new diagnostic capabilities are possible, such as determining thresholds for modification. It is conceivable that such diagnostics may be used at magnetospheric altitudes also. In such cases, the powerful ground-based transmitters can provide a new method of investigating magnetospheric structure.

Acknowledgments. We thank the Office of Naval Research and the Air Force Research Laboratory for the opportunity to use the HAARP and HIPAS research facilities. We also thank the National Aeronautics and Space Administration and the Centre National d'Etudes Spatiales for supporting the WIND spacecraft and WAVES experiment.

References

Bougeret, J.-L., M. L. Kaiser, P. J. Kellogg, R. Manning, K. Goetz, S. J. Monson, N. Monge, L. Friel, C. A. Meetre, C. Perche, L. Sitruk, and S. Hoang, WAVES: the radio and plasma wave investigation on the WIND spacecraft, *Space Sci. Rev.*,**71**, 231, 1995.

Jenkins, F. A., and H. E. White, *Fundamentals of Optics*, 4th ed., McGraw-Hill Book Company, New York, 1997.

Kaiser, M. L., M. D. Desch, J.-L. Bourgeret, R. Manning, and C. A. Meetre, WIND/WAVES observations of man-made radio transmissions, *Geophys. Res. Lett.*, **23**, 1287, 1996.

Keskinen, M. J., and S. L. Ossakow, Theories of high-latitude ionospheric irregularities, *Radio Sci.*, **18**, 1077, 1983.

Keskinen, M. J., and P. Rodriguez, Modulation instability at the upper-hybrid layer in high power radio wave ionospheric heating, *Radio Sci.*, **33**, 143, 1998.

Rodriguez, P., and E. P. Szuszczewicz, High-latitude irregularities in the lower F-region: Intensity and scale size distributions, *J. Geophys. Res.*, **89**, 5575, 1984.

Rodriguez, P., E. J. Kennedy, M. J. Keskinen, C. L. Siefring, Sa. Basu, M. McCarrick, J. Preston, M. Engebretson, M. L. Kaiser, M. D. Desch, K. Goetz, J.-L. Bougeret, and R. Manning, The WIND-HAARP experiment: initial results of high power radiowave interactions with space plasmas, *Geophys. Res. Lett.*, **25**, 257, 1998.

Tsunoda, R. T., High latitude F region irregularities: a review and synthesis, *Rev. Geophys.*,**26**,719-760, 1988.

Weber, E. J., J. A. Klobuchar, J. Buchau, H. C. Carlson, Jr., R. C. Livingston, O. de la Beaujardiere, M. McCready, J. G. Moore, G. J. Bishop, Polar cap F layer patches: Structure and dynamics, *J. Geophys. Res.*, **91**, 12,121, 1986.

Wong, A. Y., J. Carroll, R. Dickman, W. Harrison, W. Huhn, B. Lum, M. McCarrick, J. Santoru, C. Schock, G. Wong, and R. F. Wuerker, High-power radiating facility at the HIPAS observatory, *Radio Sci.*, **25**, 1269, 1990.

Figure Captions

Figure 1. The ecliptic plane projection of the WIND trajectory. The interferometer experiment was conducted on 31 December 1996. Models of the ecliptic plane intersection of the bow shock, magnetopause, and plasmapause are shown.

Figure 2. The modulation patterns of the experiment, showing the power transmission profiles of the HAARP and HIPAS, and the resulting expected reception pattern at the WIND spacecraft.

Figure 3. The observed signal intensity for the one-hour duration of the experiment. The ON-OFF modulations at the beginning and end of the experiment provide signatures of the transmitting sources.

Figure 4. Detailed plot of calculated fringe pattern compared with observed fringe pattern. At the radial distance of WIND, one fringe would have a width of about 33 km. The basic fringe structure appears to be imbedded in smaller scale irregularities.

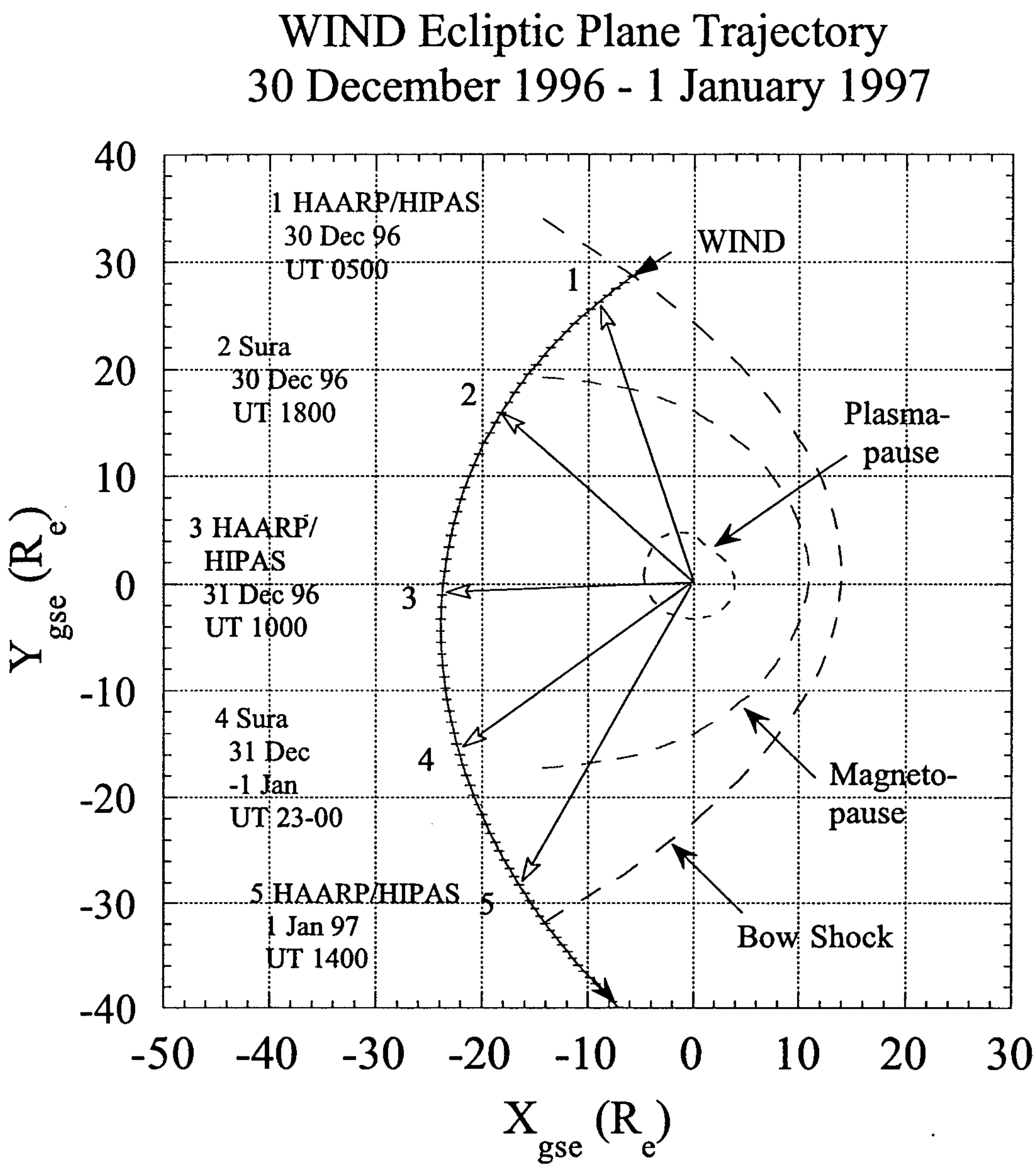
WIND Ecliptic Plane Trajectory
30 December 1996 - 1 January 1997
1 HAARP/HIPAS
30 Dec 96
UT 0500
2 Sura
30 Dec 96
UT 1800
3 HAARP/
HIPAS
31 Dec 96
UT 1000
4 Sura
31 Dec
-1 Jan
UT 23-00
5 HAARP/HIPAS
1 Jan 97
UT 1400
WIND
Plasma-
pause
Magneto-
pause
Bow Shock
1
2
3
4
5
40
30
20
10
0
-10
-20
-30
-40
-50
-40
-30
-20
-10
0
10
20
30
X_{gse} (R_e)
Y_{gse} (R_e)

Figure 1

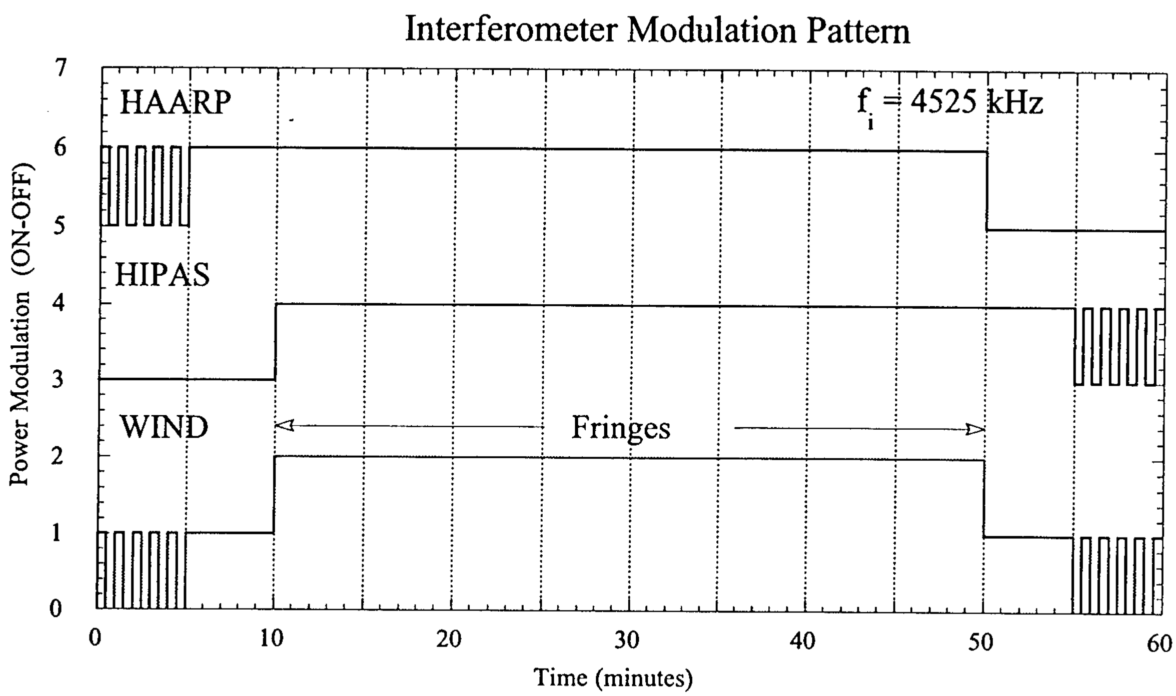
Interferometer Modulation Pattern
HAARP
f_i = 4525 kHz
HIPAS
WIND
Fringes
Power Modulation (ON-OFF)
Time (minutes)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60

Figure 2

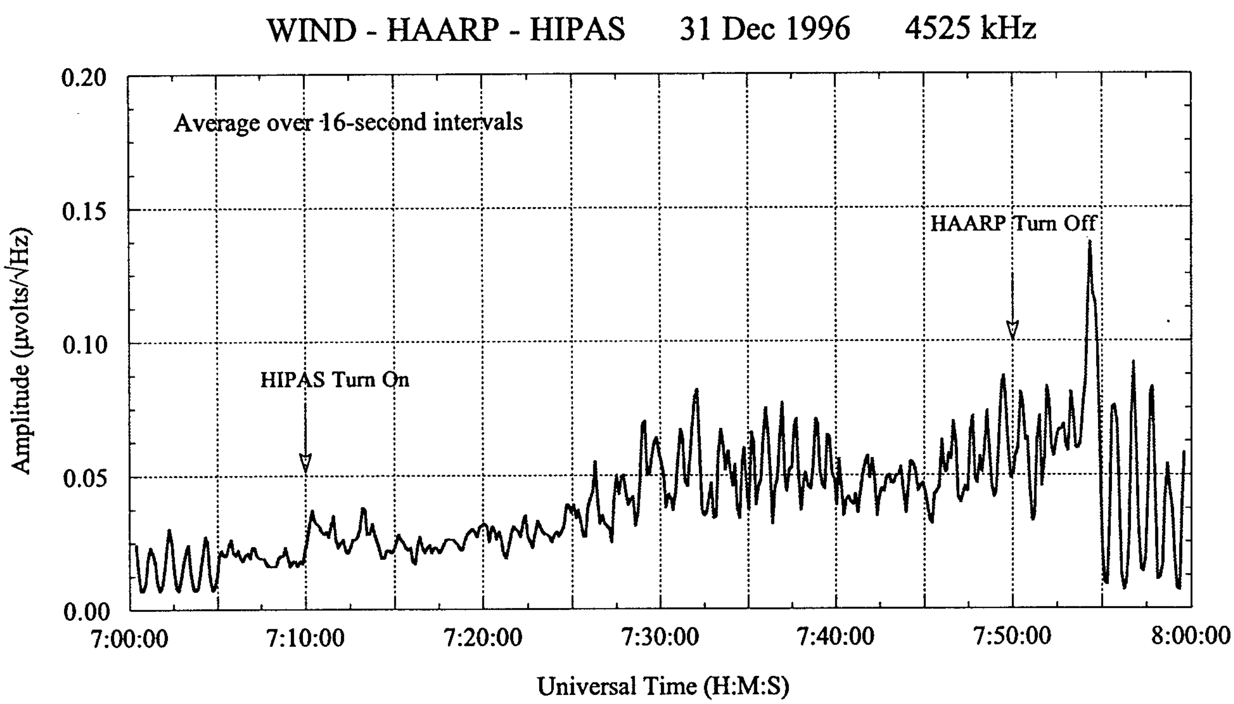
WIND - HAARP - HIPAS 31 Dec 1996 4525 kHz
Average over 16-second intervals
HAARP Turn Off
HIPAS Turn On
Amplitude (µvolts/√Hz)
0.20
0.15
0.10
0.05
0.00
7:00:00
7:10:00
7:20:00
7:30:00
7:40:00
7:50:00
8:00:00
Universal Time (H:M:S)

Figure 3

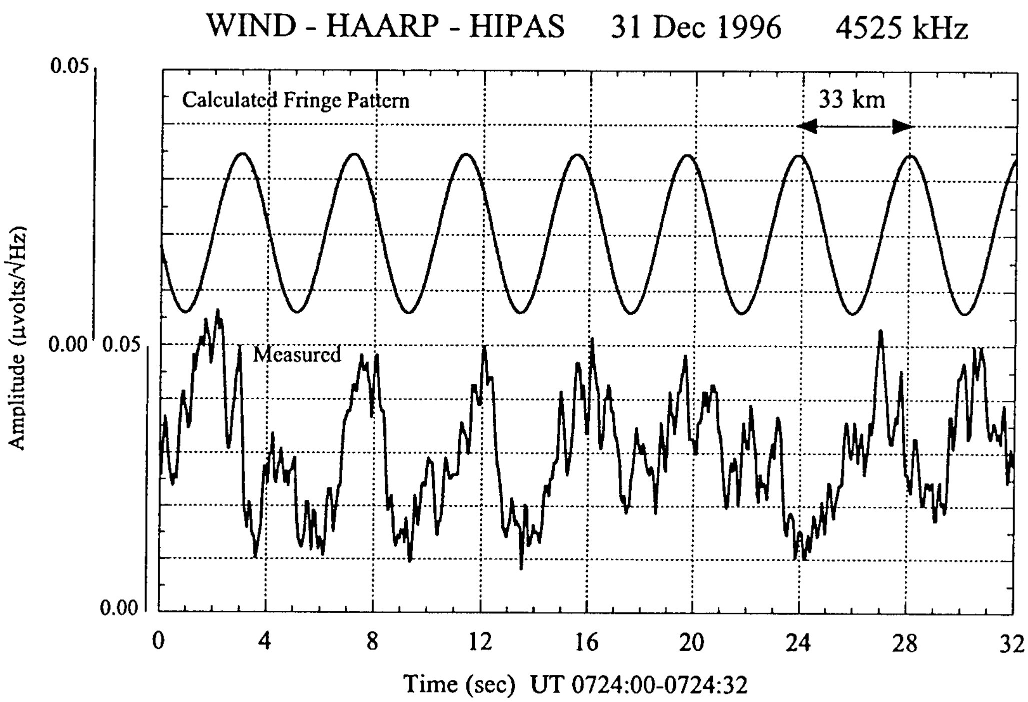
WIND - HAARP - HIPAS 31 Dec 1996 4525 kHz
Calculated Fringe Pattern
33 km
Measured
Amplitude (μvolts/√Hz)
0.05
0.00
0.05
0.00
0
4
8
12
16
20
24
28
32
Time (sec) UT 0724:00-0724:32

Figure 4